Optically transparent piezoelectric transducer for ultrasonic particle manipulation

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Letters

Optically Transparent Piezoelectric Transducer for Ultrasonic Particle Manipulation

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***Abstract*—We report an optically transparent ultrasonic device, consisting of indium-tin-oxide-coated lithium niobate (LNO), for use in particle manipulation. This device shows good transparency in the visible and near-infrared wavelengths and, acoustically, compares favorably with conventional prototype devices with silver electrodes.**

I. Introduction

The combined use of ultrasonics and optics is severely restricted by the opacity of conventional piezoelectric devices. This is of particular interest in combined acoustic and optical microparticle manipulation, for which previous attempts have required specifically designed optical systems [1] or use of an ultrasonic standing wave trap in which the active elements are located on the sides of the sample chamber [2]. The opaque nature of piezoelectric devices is also a concern in opto-acoustic imaging [3] in cases in which the laser source and an ultrasonic receiver must be positioned on the same side of the sample to be imaged. Indium tin oxide (ITO)-coated polyvinylidene fluoride (PVDF) receivers [4] have been proposed in the past, but the characteristics of PVDF limit them to passive detection. Here, we report an optically-transparent ultrasonic transducer which can be used for combined optical and acoustic trapping without the need to modify the optical system and also allows for simultaneous ultrasound and optoacoustic imaging. Use of this device opens up the possibility of using more complex optical systems such as counter-propagating traps and, crucially, still allows for through-illumination imaging methods to be used.

II. Materials and Methods

Lithium niobate (LNO), with crystal symmetry *3mm*, is well known for use in optics in devices such as Pockle's cells [5] and electro-optic devices. It also has a range of actual and potential ultrasonic applications including high-temperature nondestructive testing [6], high-resolution medical imaging [7] and focused ultrasound surgery [8]. This range of applications corresponds to the wide range of physical effects LNO displays, including piezoelectricity, pyroelectricity, optical birefringence, and second harmonic generation [5]. The geometrical form of LNO we selected for the transparent devices reported here is Y-36° cut LNO (Roditi International Corp., London, UK) because it has the highest piezoelectric thickness-mode electromechanical coupling coefficient, $k_\mathrm{T} = 0.49$.

The samples, with dimensions 10 × 10 × 0.5 mm, were coated with ITO on their major surfaces using dc magnetron sputtering (Diamond Coatings Ltd., Halesowen, UK) to produce the required solid solution of indium oxide (In_2O_3) and tin oxide (SnO_2) [9]. ITO is also widely used for transparent electrodes in liquid crystal displays, solar cells, and light-emitting diodes [10].

The thickness of ITO was not measured during deposition but was estimated as 606.3 ± 54.9 nm using results from spectrophotometry. The sheet resistance of the sample was 10 Ω/sq and the average surface roughness, R_a, was 1.69 nm. The electrical conductivity of optimized ITO is in the range of 10^4 S/cm [11], the density is 7100 kg/m^3 [12], the Young's modulus is 116 GPa [13], the Poisson ratio is 0.35 [13], and the velocity of sound, calculated by the Newton–Laplace equation, is about 4200 m/s. A photograph of a complete ITO-coated LNO sample is shown in Fig. 1.

III. Results and Discussions

A. Spectrophotometry

The samples were first tested for optical transmittance using a spectrophotometer (Jasco Inc., Easton, MD) at visible and near infrared (NIR) wavelengths to cover both imaging through the sample and NIR laser wavelengths commonly used for optical manipulation. A sample of uncoated LNO was also measured for its transmission as a comparison. The transmission spectra of the coated and uncoated wafers are shown in Fig. 2. Over both visible and NIR wavelengths, the ITO-coated LNO shows good transmittance. Around 600 and 800 nm, the ITO-coated sample is more transmissive than the uncoated sample, suggesting that the ITO acts as an anti-reflective coating at these wavelengths.

B. Electrical Impedance Spectroscopy

The ITO-coated LNO was tested for its ultrasonic response using a fiber optic hydrophone (FOH; Precision Acoustics, Dorset, UK). To calibrate the response of the

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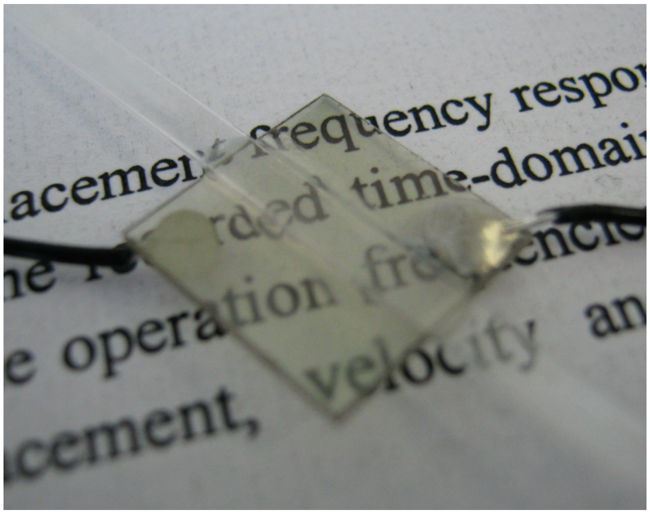

Fig. 1. A Y-36° cut lithium niobate plate coated with indium tin oxide and coupled to a glass capillary, showing its visible transparency.

ITO-coated material, a 10 × 10 × 0.5 mm sample was housed in a plastic case along with a sample of LNO of identical dimensions coated with conventionally conducting, opaque silver electrodes. The LNO samples were fixed by microballoon-filled epoxy at the edges, with air backing, to avoid dissipation of energy. The electrical impedance spectrum of each sample was recorded in air using a 4395A impedance /network /spectrum analyzer (Agilent Technologies, South Queensferry, UK) as shown in Fig. 3.

From the impedance spectra, it can be seen that the Ag-coated LNO has a slightly lower resonant frequency, attributed to the fact that it has thicker electrodes than the ITO-coated sample. The effective coupling coefficients of both transducers were calculated using the parallel resonant frequency, f_p, and series resonant frequency, f_s [14]:

$$k_\mathrm{eff} = \sqrt{(f_\mathrm{p}^2 - f_\mathrm{s}^2)/f_\mathrm{p}^2}. \quad (1)$$

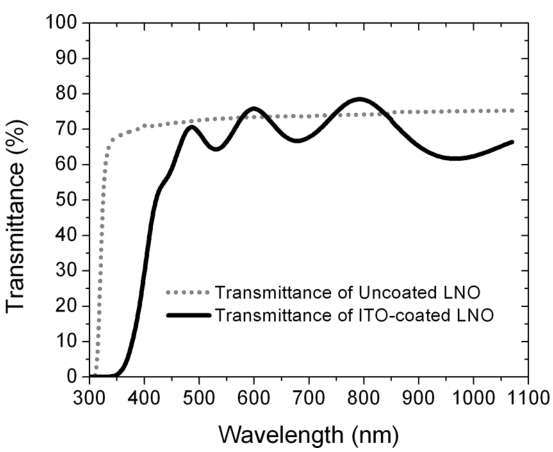

Fig. 2. Optical transmittance of the uncoated and indium tin oxide (ITO)-coated lithium niobate (LNO) showing good transparency for visible and near-IR wavelengths.

TABLE I. Resonant Frequencies and Effective Coupling Factors of Ag-Coated and Indium Tin Oxide (ITO)-Coated Lithium Niobate (LNO).

	f_s (MHz)	f_p (MHz)	k_eff
Ag-coated LNO	6.288	7.104	0.4653
ITO-coated LNO	6.498	7.253	0.4442

The calculated effective coupling coefficients show that the ITO-coated LNO has very similar performance to the Ag-coated LNO, with k_eff reduced by less than 5%, as shown in Table I; both these figures are about 10% below the value for k_T noted previously.

C. Acoustic Pressure Characterization

For pressure measurements, each sample was driven at its fundamental series resonant frequency, f_s, as listed in Table I, using an Agilent 32220A waveform generator. Both the device and the hydrophone were immersed in a water tank. The hydrophone was connected to an oscilloscope and positioned so as to receive the peak pressure signal. The signal voltage for each sample was increased in increments of 1 $\mathrm{V_{pp}}$ from 4 $\mathrm{V_{pp}}$ up to 20 $\mathrm{V_{pp}}$ and the received signal from the hydrophone recorded at each interval. A total of five sets of measurements were carried out and the standard deviations were calculated. These recorded voltages were then converted to the pressure according to the manufacturer's calibration of the hydrophone sensitivity at the working frequency. Fig. 4 compares the pressure produced by the samples. The base noise level of the hydrophone when not receiving a signal has been subtracted from the measured signal.

The pressure measurements show an adequate response from the ITO-coated LNO in comparison to the Ag-coated sample, in turn suggesting that using ITO is a viable alternative to conventional opaque electrodes in applications in which a transparent transmitting transducer is required, without a significant sacrifice in performance—less than 4 dB in the present case. Specifically, for microfluidic resonant devices, an ultrasonic standing wave with a pressure

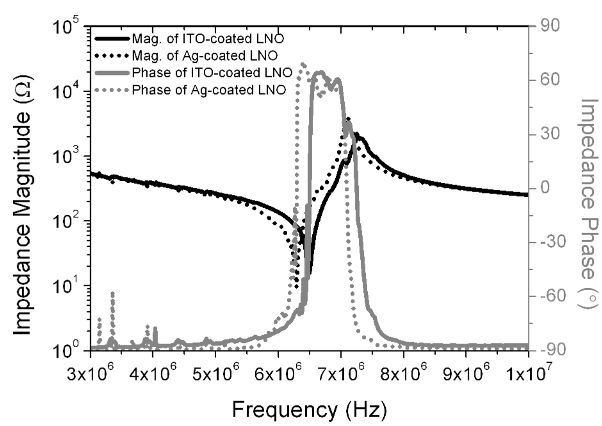

Fig. 3. Impedance magnitude and phase spectra of indium tin oxide (ITO)-coated lithium niobate (LNO) compared with Ag-coated ITO.

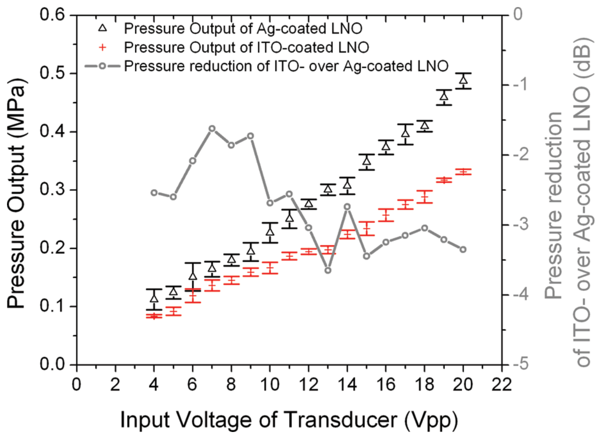

Fig. 4. The pressure output of indium tin oxide (ITO)-coated lithium niobate (LNO) compared with Ag-coated LNO.

amplitude of 0.35 to 0.5 MPa can generate a radiation force of the order of 100 pN on a 10-μm-diameter polystyrene sphere [15]. In this case, if the ITO-coated LNO is coupled to a resonant cavity with a conventional Q-factor, i.e., $50 < Q < 1000$ [16], the pressure in the cavity would be sufficient to manipulate the microparticles.

IV. Conclusions

In conclusion, we have shown that ITO-coated LNO transducers have good transparency in the visible and NIR regions of the optical spectrum and can produce ultrasonic pressures which are similar to those produced with commonly used silver electrodes. The optical transmission could be further improved by using refractive-index-matched ITO. Use of these devices opens up the possibility of configuring a wide range of hybrid ultrasonic–optical systems without the restrictions associated with using opaque ultrasonic transducers.

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References

[1] G. Thalhammer, R. Steiger, M. Meinschad, M. Hill, S. Bernet, and M. Ritsch-Marte, “Combined acoustic and optical trapping,” *Biomed. Opt. Express*, vol. 2, no. 10, pp. 2859–2870, 2011.
[2] C. R. P. Courtney, B. W. Drinkwater, C. E. M. Demore, S. Cochran, A. Grinenko, and P. D. Wilcox, “Dexterous manipulation of microparticles using Bessel-function acoustic pressure fields,” *Appl. Phys. Lett.*, vol. 102, no. 12, art.no. 123508, 2013.
[3] L. V. Wang, “Multiscale photoacoustic microscopy and computed tomography,” *Nat. Photonics*, vol. 3, no. 9, pp. 503–509, Aug. 2009.
[4] J. J. Niederhauser, M. Jaeger, M. Hejazi, H. Keppner, and M. Frenz, “Transparent ITO coated PVDF transducer for optoacoustic depth profiling,” *Opt. Commun.*, vol. 253, no. 4–6, pp. 401–406, Sep. 2005.
[5] R. S. Weis and T. K. Gaylord, “Lithium niobate: Summary of physical properties and crystal structure,” *Appl. Phys. A*, vol. 37, no. 4, pp. 191–203, 1985.
[6] N. Schmarje, K. J. Kirk, and S. Cochran, “1-3 Connectivity lithium niobate composites for high temperature operation,” *Ultrasonics*, vol. 47, no. 1–4, pp. 15–22, Dec. 2007.
[7] J. Cannata, T. Ritter, W.-H. Chen, R. Silverman, and K. Shung, “Design of efficient, broadband single-element (20–80 MHz) ultrasonic transducers for medical imaging applications,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 50, no. 11, pp. 1548–1557, 2003.
[8] S. Kotopoulis, H. Wang, S. Cochran, and M. Postema, “Lithium niobate transducers for MRI-guided ultrasonic microsurgery,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 58, no. 8, pp. 1570–1576, Aug. 2011.
[9] H. Liu, V. Avrutin, N. Izyumskaya, Ü. Özgür, and H. Morkoç, “Transparent conducting oxides for electrode applications in light emitting and absorbing devices,” *Superlattices Microstruct.*, vol. 48, no. 5, pp. 458–484, Nov. 2010.
[10] C. G. Granqvist and A. Hultaker, “Transparent and conducting ITO films: New developments and applications,” *Thin Solid Films*, vol. 411, no. 1, pp. 1–5, 2002.
[11] T. Minami, “New n-type transparent conducting oxides,” *MRS Bull.*, vol. 25, no. 8, pp. 38–44, 2000.
[12] H. Tian, D. Xie, Y. Yang, T.-L. Ren, Y.-F. Wang, C.-J. Zhou, P.-G. Peng, L.-G. Wang, and L.-T. Liu, “Transparent, flexible, ultrathin sound source devices using indium tin oxide films,” *Appl. Phys. Lett.*, vol. 99, no. 4, art. no. 043503, 2011.
[13] D. G. Neerinck and T. J. Vink, “Depth profiling of thin ITO films by grazing incidence X-ray diffraction,” *Thin Solid Films*, vol. 278, no. 1, pp. 12–17, 1996.
[14] *IEEE Standard on Piezoelectricity*, ANSI/IEEE Std. 176-1987, 1987.
[15] P. Glynne-Jones, C. E. M. Démoré, C. Ye, Y. Qiu, S. Cochran, and M. Hill, “Array-controlled ultrasonic manipulation of particles in planar acoustic resonator,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 59, no. 6, pp. 1258–1266, Jun. 2012.
[16] R. Barnkob, P. Augustsson, T. Laurell, and H. Bruus, “Measuring the local pressure amplitude in microchannel acoustophoresis,” *Lab Chip*, vol. 10, no. 5, pp. 563–570, 2010.